

# The properties of single WO stars

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**Abstract.** The enigmatic oxygen sequence Wolf-Rayet (WO) stars represent a very late stage in massive star evolution, although their exact nature is still under debate. The spectra of most of the WO stars have never been analysed through detailed modelling with a non-local thermodynamic equilibrium expanding atmosphere code. Here we present preliminary results of the first homogeneous analysis of the (apparently) single WOs.

**Keywords.** stars: Wolf-Rayet, stars: fundamental parameters, stars: evolution, stars: individual (WR102, WR142, WR93b, BAT99-123, LH41-1042, DR1), stars: abundances

## 1. Introduction

The nature of the very rare WO stars is still under debate. Although it is clear that they are highly evolved massive stars, their evolutionary connection to the more common carbon sequence Wolf-Rayet (WC) stars remains unclear. To unravel their nature, we are undertaking a project targeting all the known WO stars. Here we present preliminary results of the first homogeneous analysis of the single WOs.

## 2. Observational sample and spectral classification

We have obtained the near-ultraviolet to near-infrared spectra of all known WO stars using the X-Shooter spectrograph on ESO's Very Large Telescope (except for the recently discovered WO star in the LMC; Massey et al. 2014). The spectra cover a wavelength range from 3000 to 25 000 Å at a resolving power of  $R \sim 8000$ . The sample consists of three stars in the Milky Way (MW), two in the Large Magellanic Cloud (LMC), and one in IC 1613. The two WO stars in a binary system have also been observed, but are not analysed in this work. Figure 1 shows the X-Shooter spectra of all WO stars.

The spectral type of the single stars is determined using the classification criteria from Crowther et al. (1998). These are based on the equivalent width ratios of OVI 3811-34 Å / Ov 5590 Å and OVI 3811-24 Å / CIV 5801-12 Å, as well as the full width at half maximum of CIV 5801-12 Å. The derived spectral types are given in Table 1.

## 3. Modelling and conclusions

We model the X-Shooter spectra using CMFGEN (Hillier & Miller 1998) following the method described in Tramper et al. (2013). While the observed strong OVI 3811-34 Å

**Table 1.** Spectral types and preliminary parameters of the single WO stars.

ID	ID ( <i>figure</i> )	SpT	$\log L$ ( $L_{\odot}$ )	$T_*$ (kK)	$X_C$	$X_O$
WR102	WO-MW-1	WO2	5.45	210	0.62	0.25
WR142	WO-MW-2	WO2	5.63	200	0.54	0.21
WR93b	WO-MW-3	WO3	5.30	160	0.53	0.18
BAT99-123	WO-LMC-1	WO3	5.26	170	0.55	0.15
LH41-1042	WO-LMC-2	WO4	5.26	150	0.60	0.18
DR1	WO-IC1613-1	WO3	5.68	150	0.46	0.10

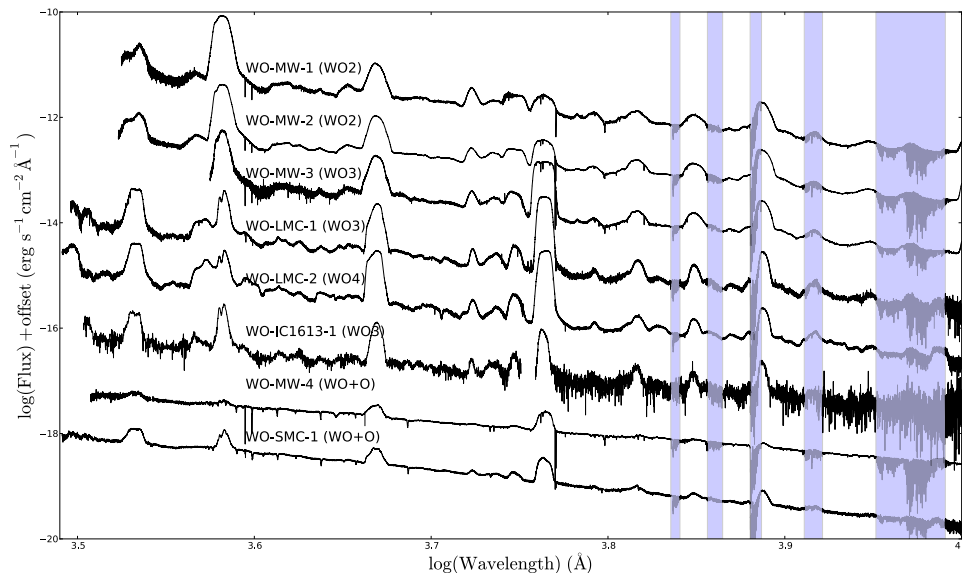
*Notes:* Results for DR1 from Tramper et al. (2013). Values for all other stars are preliminary and subject to change.

emission is not (fully) reproduced, the rest of the spectrum is very well represented by our models. Preliminary parameters derived from the modelling are given in Table 1. Note that the models are currently still being refined, and these values are subject to small changes.

The surface abundances of the WO stars indicate that they have at least burned two-third of the helium in their core, and are expected to explode as type Ic supernovae within  $10^5$  years. Most evolved is WR102, which may have already exhausted the helium in its core and will likely end its life in less than  $10^4$  years. Compared to WC stars, the WO stars are hotter and show higher surface abundances of carbon and oxygen.

## References

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**Figure 1.** Dereddened, flux-calibrated spectra of the WO stars in the 3 000-10 000 Å wavelength range. The shaded areas indicate regions with telluric features. Labels are defined in Table 1.